Foundation of Cryptography (0368-4162-01), Lecture 7

MACs and Signatures

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Section 1

Message Authentication Code (MAC)

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- **Consistency:** $\mathsf{Vrfy}(k, m, t) = 1$ for any $k \in \mathsf{Supp}(\mathsf{Gen}(1^n))$, $m \in \{0,1\}^n$ and $t = \mathsf{Mac}(k, m)$

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- **Unforgability:** For any oracle-aided PPT A:

$$\Pr\left[k \leftarrow \mathsf{Gen}(1^n); (m, t) \leftarrow \mathsf{A}^{\mathsf{Mac}_k, \mathsf{Vrfy}_k}(1^n) : \mathsf{Vrfy}_k(m, t) = 1 \wedge \mathsf{Mac}_k \text{ was not asked on } m\right] \leq \mathsf{neg}(n)$$

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- Will focus on bounded length messages (specifically n), and then show how to move to any length

Bounded MACs

Definition 2 (ℓ-time MAC)

Same as in Definition 1, but security is only required against ℓ-query adversaries.

Zero-time MAC

Construction 3 (One-time MAC)

- $\mathsf{Gen}(1^n)$: outputs $k \leftarrow \{0,1\}^n$
- $\mathsf{Mac}(k, m) = k$
- $\mathsf{Vrfy}(k, m, t) = 1$, iff $t = k$

ℓ-times MAC

Definition 4 (ℓ-wise independent)

A function family $\mathcal{H}$ from $\{0,1\}^n$ to $\{0,1\}^m$ is ℓ-wise independent, where $\ell \in \mathbb{N}$, if for every distinct $x_1, \ldots, x_\ell \in \{0,1\}^n$ and every $y_1, \ldots, y_\ell \in \{0,1\}^m$, it holds that $\Pr_{h \leftarrow \mathcal{H}}[h(x_1) = y_1 \wedge \cdots \wedge h(x_\ell) = y_\ell] = 2^{-\ell m}$.

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Construction 5 (ℓ-time MAC)

Let $\mathcal{H} = \{\mathcal{H}_n \colon \{0,1\}^n \mapsto \{0,1\}^n\}$ be an efficient ℓ-wise independent function family.

- $\mathrm{Gen}(1^n)$: outputs $h \leftarrow \mathcal{H}_n$
- $\mathrm{Mac}(h, m) = h(m)$
- $\mathrm{Vrfy}(h, m, t) = 1$, iff $t = h(m)$

OWF $\Longrightarrow$ MAC

Construction 6 (PRF-based MAC)

Same as Construction 5, but uses function $\mathcal{F} = \{\mathcal{F}_n \colon \{0,1\}^n \mapsto \{0,1\}^n\}$ instead of $\mathcal{H}$.

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Claim 7

Assuming that $\mathcal{F}$ is a PRF, then Construction 6 is a MAC.

Proof:

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Proof: Easy to prove if $\mathcal{F}$ is a family of random functions. Hence, also holds in case $\mathcal{F}$ is a PRF. $\square$

Length restricted MAC $\Longrightarrow$ MAC

Construction 8 (Length restricted MAC $\Longrightarrow$ MAC)

Let $(\text{Gen}, \text{Mac}, \text{Vrfy})$ be length restricted MAC with $d(n) = n$, and let $\mathcal{H} = \{\mathcal{H}_n \colon \{0,1\}^* \mapsto \{0,1\}^n\}$ be an eff. function family.

- $\text{Gen}'(1^n)$: $k \leftarrow \text{Gen}(1^n)$, $h \leftarrow \mathcal{H}_n$. Set $k' = (k, h)$
- $\text{Mac}'_{k,h}(m) = \text{Mac}_k(h(m))$
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Assume $\mathcal{H}$ is “collision resistant", then $(\mathrm{Gen}', \mathrm{Mac}', \mathrm{Vrfy}')$ is a MAC.

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Definition 10 (collision resistant hash family (CRH))

A function family $\mathcal{H} = \{\mathcal{H}_n \colon \{0,1\}^* \mapsto \{0,1\}^n\}$ is collision resistant, if

$$\Pr[h \leftarrow \mathcal{H}_n, (x, x') \leftarrow \mathsf{A}(1^n, h) \colon x \neq x' \in \{0,1\}^* \\ \wedge h(x) = h(x')] \leq \operatorname{neg}(n)$$

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Proof: (of Claim 9) HW

Section 2

Signature Schemes

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- Oracle access to Vrfy is not given
- Strong signatures: impossible to generate *any* new valid signatures (even for message for which a signature was asked)

Section 3

OWF $\implies$ Signature

One Time Signatures

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Definition 13 (length restricted, one time signatures)

Same as Definition 26, but A can only for signatures of predetermined length (in our case *n*).

- Assuming CRH exists: length restricted, one time signatures $\Longrightarrow$ one time signatures.

OWF $\implies$ length restricted, One Time Signature

Construction 14 (length restricted, one time signature)

Let $f\colon \{0,1\}^n \mapsto \{0,1\}^n$.

1. Gen(1^n): $s_1^0, s_1^1, \ldots, s_n^0, s_n^1 \leftarrow \{0,1\}^n$, let $s = (s_1^0, s_1^1, \ldots, s_n^0, s_n^1)$ and $v = (v_1^0 = f(s_1^0), v_1^1 = f(s_1^1), \ldots, v_n^0 = f(s_n^0), v_n^1 = f(s_n^1))$
2. Sign(s, m): Output $(s_1^{m_1}, \ldots, s_n^{m_n})$
3. Vrfy$(v, m, \sigma = (\sigma_1, \ldots, \sigma_n))$ check that $f(\sigma_i) = v_{m_i}$ for all $i \in [n]$

OWF $\implies$ length restricted, One Time Signature

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2. $\mathrm{Sign}(s, m)$: Output $(s_1^{m_1}, \ldots, s_n^{m_n})$
3. $\mathrm{Vrfy}(v, m, \sigma = (\sigma_1, \ldots, \sigma_n))$ check that $f(\sigma_i) = v_{m_i}$ for all $i \in [n]$

Lemma 15

Assume that f is a OWF, then scheme from Construction 14 is a length restricted one-time signature scheme

Proving Lemma 15

Let a PPT A, $\mathcal{I} \subseteq \mathbb{N}$ and $p \in$ poly that break the security of Construction 14, we use A to invert f.

Algorithm 16 (Inv)

Input: $y \in \{0,1\}^n$

1. Choose $(s, v) \leftarrow Gen(1^n)$ and replace $v^{i^*}_{j^*}$ for a random $i^* \in [n]$ and $j^* \in \{0,1\}$, with y.
2. If $A(1^n, v)$ asks to sign message $m \in \{0,1\}^n$ with $m_{i^*} = j^*$ abort, otherwise use s to answer the query.
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Stateful schemes (also known as, Memory-dependant schemes)

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- Make sense in many applications (e.g., , smartcards)
- We'll use it a building block for building a stateless scheme

Naive construction

Let (Gen, Sign, Vrfy) be a one-time signature scheme.

Construction 18 (Naive construction)

1. $\mathrm{Gen}'(1^n)$ outputs $(s, v) = \mathrm{Gen}(1^n)$.
2. $\mathrm{Sign}_s(m_i)$, where m_i is i'th message to sign:
   Let $((m_1, \sigma'_1), \ldots, (m_{i-1}, \sigma'_{i-1}))$ be the previously signed pairs of messages/signatures.
   1. Let $(s_i, v_i) \leftarrow \mathrm{Gen}(1^n)$
   2. Let $\sigma_i = \mathrm{Sign}_{s_{i-1}}(m_i, v_i)$, where $s_0 = s$, and output $\sigma'_i = (\sigma'_{i-1}, m_i, v_i, \sigma_i)$.
3. $\mathrm{Vrfy}'_v(m, \sigma' = (m_1, v_1, \sigma_1), \ldots, (m_i, v_i, \sigma_i))$:
   1. Check that $m_i = m$.
   2. $\forall j \in [i]$, verify that $\mathrm{Vrfy}_{v_{i-1}}((m_i, v_i), \sigma_i) = 1$, where $v_0 = v$.

Stateful schemes

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Assume that $(\mathsf{Gen}, \mathsf{Sign}, \mathsf{Vrfy})$ *is one time signature scheme, then* $(\mathsf{Gen}', \mathsf{Sign}', \mathsf{Vrfy}')$ *is a stateful signature scheme.*

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Proof: Let a PPT A', $\mathcal{I} \subseteq \mathbb{N}$ and $p \in \text{poly}$ that breaks the security of $(\mathsf{Gen}', \mathsf{Sign}', \mathsf{Vrfy}')$, we present a PPT A that breaks the security of $(\mathsf{Gen}, \mathsf{Sign}, \mathsf{Vrfy})$.

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We assume for simplicity that p also bounds the query complexity of A'

Proving Lemma 19 cont.

Let (the r.v) $(m, \sigma = (m_1, v_1, \sigma_1), \ldots, (m_q, v_q, \sigma_q))$ be the pair output by A'.

Proving Lemma 19 cont.

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Whenever A' breaks the scheme, $\exists i \in [q]$ s.t. :

1. Sign′ *was not* asked by A' on m_i.
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Proof: Let i be the maximal index such that condition (2) holds (cannot be q).$\square$

Let i be the index guaranteed by Claim 20 in a successful attack of A$'$.

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Hence, $\text{Sign}_{s_i}(\sigma_i, m_i^* = (m_i, v_i)) = 1$, where s_i is the signing key generated by Sign'_s when signing m_{i-1}, and Sign_{s_i} was not queried (by Sign'_s) on m_i^*.

Definition of A

We define algorithm A as follows:

Algorithm 21 (A)

Input: v, 1^n

Oracle: Sign_s

1. Choose $i^* \leftarrow [p = p(n)]$ and $(s', v') \leftarrow \mathrm{Gen}'(1^n)$.
2. Emulate a random execution of $\mathrm{A}'^{\mathrm{Sign}'_{s'}}$ with a single twist:
   - On the i^*'th call to $\mathrm{Sign}'_{s'}$, set $v_{i^*} = v$ (rather then choosing it via Gen)
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3. Let $(m, \sigma = (m_1, v_1, \sigma_1), \ldots, (m_q, v_q, \sigma_q)) \leftarrow \mathrm{A}'$
4. Output $((m_{i^*}, v_{i^*}), \sigma_{i^*})$ (abort if $i^* > q$))

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- The emulated game $\mathrm{A}'^{\mathrm{Sign}'_{s'}}$ has the “right" distribution.

Analysis of A

Let $i(m, \sigma)$ be the index guaranteed by Claim 20 (set to $\perp$, if A′ dos not break the scheme).

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Hence, for any $n \in \mathcal{I}$

$$
\begin{aligned}
&\Pr[\mathsf{A}(1^n) \text{ breaks } (\mathsf{Gen}, \mathsf{Sign}, \mathsf{Vrfy})] \\
&\quad \geq \quad \Pr_{i^* \leftarrow [p = p(n)]}[i = i(m, \sigma)] \\
&\quad \geq \quad \frac{1}{p} \cdot \Pr[\mathsf{A}' \text{ breaks } (\mathsf{Gen}', \mathsf{Sign}', \mathsf{Vrfy}')] \geq \frac{1}{p(n)^2}
\end{aligned}
$$

“Somewhat"-Stateful Schemes

A one-time scheme (Gen, Sign, Vrfy), and $\ell = \ell(n) \in \omega(\log n)$

Construction 22

- $\mathsf{Gen}'(1^n)$: output $(s, v) \leftarrow \mathsf{Gen}(1^n)$.
- $\mathsf{Sign}_s(m)$: choose $r = (r_1 \ldots, r_\ell) \leftarrow \{0,1\}^\ell$ and let $(s_\lambda, v_\lambda) = (s, v)$
  1. For $i = 0$ to $\ell - 1$: if $a_{r_{1,\ldots,i}}$ was not set:
     1. For $j \in \{0,1\}$, let $(s_{r_{1,\ldots,i},j}, v_{r_{1,\ldots,i},j}) \leftarrow \mathsf{Gen}(1^n)$
     2. $\sigma_{r_{1,\ldots,i}} = \mathsf{Sign}_{s_{r_{1,\ldots,i}}}(v_{r_{1,\ldots,i},0}, v_{r_{1,\ldots,i},1})$
     3. $a_{r_{1,\ldots,i}} = \left(v_{r_{1,\ldots,i},0}, v_{r_{1,\ldots,i},1}, \sigma_{r_{1,\ldots,i}}\right)$
  2. Output $(r, a_\lambda, a_{r_1}, \ldots, a_{r_{1,\ldots,\ell-1}}, \sigma = \mathsf{Sign}_{s_r}(m))$
- $\mathsf{Vrfy}'_v(m, \sigma' = (r, a_\lambda, a_{r_1}, \ldots, a_r, \sigma)$:
  1. $\forall i \in \{0, \ldots, \ell - 1\}$, verify that $\mathsf{Vrfy}_{v_{r_{1,\ldots,i}}}(a_{r_{1,\ldots,i}}) = 1$.
  2. Verify that $\mathsf{Vrfy}_{v_r}(m, \sigma) = 1$

Somewhat-Stateful Schemes

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Lemma 23

Assume that $(\mathsf{Gen}, \mathsf{Sign}, \mathsf{Vrfy})$ *is one time signature scheme, then* $(\mathsf{Gen}', \mathsf{Sign}', \mathsf{Vrfy}')$ *is a stateful signature scheme.*

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Inefficient scheme:
Let $\Pi_{\ell,q}$ be the set of random functions from $\bigcup_{i\in[\ell]}\{0,1\}^i$ to $\{0,1\}^q$.

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Efficient scheme: use PRF

Without CRH

Definition 24 (target collision resistant (TCR))

An function family $\mathcal{H} = \{\mathcal{H}_n\}$ is target collision resistant, if for any PPT A: $\Pr[x \leftarrow A(1^n), h \leftarrow \mathcal{H}_n : x' \leftarrow A(x, h) : x \neq x' \wedge h(x) = h(x')] \leq \text{neg}(n)$

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Theorem 25

OWFs imply TCR.

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Proof: ?

- Reduction to stateless scheme as in the CRH based scheme